INTRODUCTION TO AND EVALUATION OF HOME ENERGY MANAGEMENT SYSTEMS (HEMS)

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Executive Summary

Over the course of the Energy Policy and Climate (EPC) program, I spent a formidable amount of time analyzing intelligent energy network market trends and policy implications. From studying the U.S. DOE's Smart Grid Investment Grant Program (SGIG), researching environmental monitoring technologies, and presenting case studies for smart parking solutions, I became infatuated with the role that emerging technologies, e.g., artificial intelligence, can play in today's and future energy systems. By putting my professional and academic curiosity into the capstone project, I had an opportunity to culminate all this work into a final project for not only furthering my understanding but to enhance the current literature on this energy paradigm shift.

This paper, in particular, explores home energy management system (HEMS) literature for methods and criteria to determine the effectiveness of various HEMS architectures and applications. By tailoring these findings to analyzed load profile data, this paper presents meaningful opportunities where residential consumer energy technology can create value both now and in the future to lower energy use at certain times of the day, match demand with renewable resources on the grid, and evolve capabilities to create a consumer home energy management market. This paper will further emphasize the benefits of using HEMS technology by discussing what a HEMS is, the different business services and applications it provides, how it relates to an average household, and the comparative advantages between the Northeast and West geographic regions and hot and cold climates.

Keywords: home energy management system, energy efficiency, comparative analysis

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Introduction

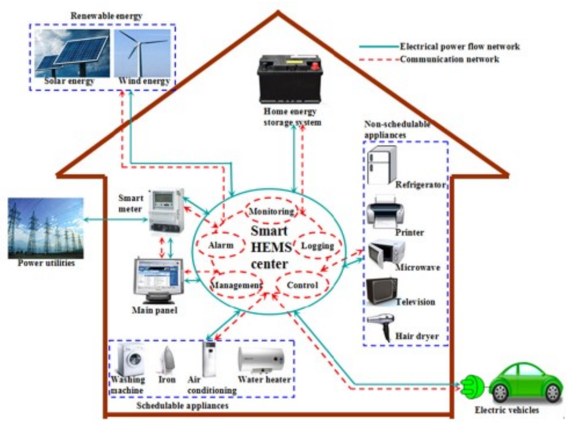
As the new energy economy emerges and renewable resources take lead in power generation, advances in technology to analyze energy load data will be a primary factor in accelerating energy efficiency initiatives, conservation strategies, and sustainability. New consumer technology in the residential household accelerates this by providing a foundation for distributed energy resources (DER) through data collection and dissemination. Coupled with the electrification of everything movement, there is greater value now and in the future to lower energy use at certain times of the day, match demand with renewables hitting the grid, and evolve capabilities to create a consumer home energy management market. This emerging market presents an opportunity to develop home energy management systems that complement these trends. As noted by Choi (2019), "home energy management systems (HEMS) encompass smart appliances, heating, ventilation, air conditioning, and distributed energy resources in homes, buildings, and apartment complexes" (Choi, 113, 2019).

The purpose of this report is to introduce and evaluate the potential role of HEMS services today as well as consider how they may evolve. To do this, this paper will address four main questions: (1) what is a HEMS at a system level and at a component level, (2) what are the different business services and applications a HEMS can provide, (3) how does an average household consume energy broken down by end-use appliance, and (4) how can a HEMS enable a more efficient residential energy consumption pattern by both region and climate.

I. What is a Home Energy Management System (HEMS)?

In order to introduce why a HEMS can provide value to residential consumers, it is important to recognize how renewable resources, such as wind and solar power, are intermittent;

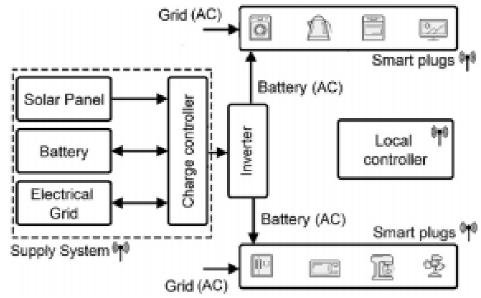
therefore, strategies to coordinate energy supply and demand between users and the utility will be vital in addressing energy imbalances between the electricity grid and point of consumption. For example, by collecting and analyzing load profile data, an energy service provider can create insights into how the consumer behaves, leading to opportunities for real-time energy management, via logging, control, and management functions. Incorporating this data into energy markets can support the delivery of more personalized product or service offerings, which will ideally improve comfort without reducing the quality of service for the customer. More specifically, "HEMS are defined as technology that consists of hardware and software, which are integrated to monitor energy usage, provide feedback on energy consumption, and enhance control over energy-consuming appliances and devices" (Randall, 1, 2017). Figure 1, below, is an overall architecture of a HEMS.



(Figure 1, Overall Architecture of a HEMS, Zhou et al.)

As can be seen in figure 1, the overall architecture, at a system level, leverages both electric power flow and information communication networks. With regards to the electric power flow network, there are two very distinct sources of power generation: (i) from the electricity grid or (ii) from distributed energy resources; the latter most commonly involve solar photovoltaic (PV) systems. "Owing to its easy installation and maintenance, solar PV is quite practical to incorporate into smart home architecture due to its suitability with common home energy storage systems (HESS), which can store the energy for future or emergency use, as well as improve network control" (Zhou et al., 35, 2016). As Greentech Media Research recently noted, "the biggest impact of distributed energy resources will be in how utilities plan, invest, operate, and maintain their distribution grids" (St. John, 2018). Taking both of these points together, this paper argues that electricity grids will continue to play a vital role in managing the acceleration of energy infrastructure at the edge, but they will also require more sensing and measurement capabilities in order to regulate the frequency and flow of electricity, such as by using more power inverter and charge controller technology.

There are also various levels of data and information flows that must be addressed, and this is where the communication network fits in. The communication network system, at a high-level, is centered around the concept of bi-directional information exchange. In other words, there is a two-way flow of information within the household and between the household and the utility. The primary enablers of this exchange are the load controller and the smart plug. As figure 2 demonstrates, "wireless communication between the local controller and the smart plug acts as a vehicle to analyze and control the consumption of each individual electrical appliance" (Shakeri et al., 111, 2018).

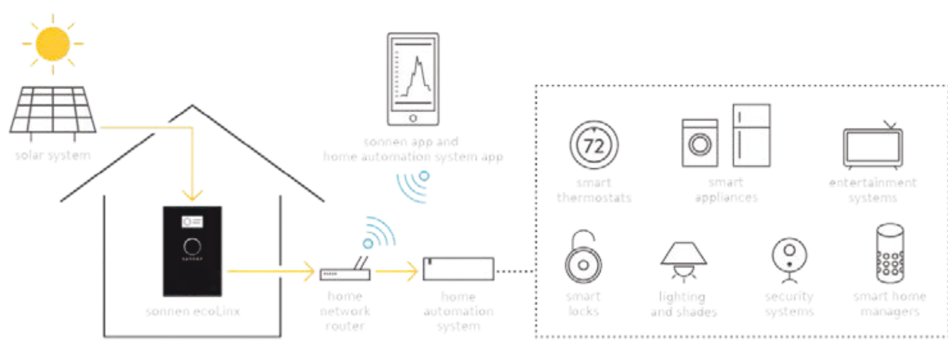


(Figure 2, Schematic of a Smart Home, Shakeri et al.)

Solar PV

A standard solar PV panel, or module, includes a layer of silicon cells, a frame, and various wiring to allow a current to flow. As EnergySage describes, “when light interacts with a silicon cell, it causes electrons to be set into motion, which initiates a flow of electric current, i.e., a photovoltaic effect” (Richardson, 2019). On-site, or distributed, solar power is often applicable to a smart HEMS and can be cost-effective in the long run depending on the location and cost structure.

For example, Sonnen, a solar manufacturer, recently announced an energy automation system that combines PV panels, energy storage, and smart circuits to automate energy optimization. “ecoLinx, the new energy automation system by Sonnen, includes smart circuit breakers that measure and record power usage. This data can be combined with information on solar power production to help users make the most out of their solar power” (Primex, 2018).



(Figure 3, How Sonnen ecoLinx Works, Sonnen)

On the other hand, solar power cannot generate power at night or whenever the sun is not shining, so HESS, including the potential use of battery energy management systems, will play a vital role to not only store the excess solar power but to provide a wide range of business services that will be discussed later in this paper.

Home Energy Storage System (HESS)

The increasing penetration of solar PV into the residential energy supply space has led to a growing interest in the potential use of emerging energy storage devices to capture any excess solar power not consumed at the point of production. There are many advances being made in energy storage chemistries, e.g., lithium-ion, that have allowed for growth in the HESS field. As McKinsey and Company notes, “annual installations of residential energy storage systems in the United States have jumped from 2.25 mega-watt hours (MWh) in 2014 to 185 MWh in 2018. Moreover, integrated installations of solar and storage equipment costs less and allows even more flexibility in adjusting supply and demand to reflect market prices, potentially reducing the cost of a battery system by more than 25 percent compared with a stand-alone battery storage pack” (Finkelstein et al., 2019).

A popular new storage system is that from Enphase Energy. Enphase Energy’s storage system is able to provide time-of-use optimization, backup power, and off grid applications. It is a modular battery storage system designed for residential customers with and without grid-tied solar power systems, which will play an important role in integrating on-site solar PV power into the residential energy space (Enphase Energy, 2019).

Electricity Grid

In a traditional electricity grid architecture, all power is generated centrally and controlled through the transmission networks to the distribution networks on through to the end-user. However, with DERs, such as solar PV and HESS, power can flow in both directions to and from the electricity grid, which may create a host of reliability issues. Therefore, the most important piece will be the grid’s distribution network, which distributes electricity to homes for end-use products. In order to manage this disruption to the conventional model, there will need to be new infrastructure, such as charge controllers and power inverters, and innovative business models that compensates the utility due to lower utilization of the distribution network with more on-site solar PV.

Charge Controller

Since there is an accelerating amount of on-site solar power and energy storage deployment, energy service providers will be required to deliver a series of tools and equipment to maintain network reliability, including the use of a charge controller. The primary function of any charge controller is to regulate the amount of charge going to a battery so that the battery does not over-charge, which can damage the battery and reduce the efficiency of the complementary on-site solar PV, as shown in figure 4.

(Figure 4, Block Diagram of a Charge Controller Arrangement, Salahuddin)

Power Inverter

Solar power inverters are a crucial component of any solar energy system and primarily serves to change direct current (DC) output into alternating current (AC). AC is the standard used by most all commercial appliances, so it is vital in connecting the generated electricity to the end-use product. Conventional string solar power inverters have traditionally not been able to provide the level of service required of new energy technologies, but more advanced solar power inverters, e.g., microinverters, are starting to improve on a number of other capabilities, such as ensuring an optimal level of performance, data monitoring, and utility controls.

Enphase Energy, as previously discussed in the solar PV section, is also the leading microinverter manufacturer. As Enphase Energy points out, "in conventional inverter systems, when one panel fails, the whole system goes out. Or when one panel's output drops – as a result of fallen leaves, a passing cloud, or some other unavoidable factor – the system's overall performance drops to match the lowest-performing panel. With microinverters, each panel operates independently – so no matter what happens to any one panel, the rest of your system continues working" (Enphase Energy, 2019).

Local Controller

The purpose of the local controller is to serve as a central hub for data collection and dissemination, which is also accessible by the utility, via a cloud-based platform. By connecting the user to the utility, the energy service provider is able to transmit signals that prioritize the best sources of supply or a price signal to adjust energy load during peak or off-peak hours. "When the smart plug receives a request signal from the local controller, it sends a signal to the related appliance to operate the device on the following options like battery, grid, or even to curtail for some time if needed" (Shakeri et al., 111, 2018). Therefore, the local controller enables the bilateral communication of data flows and is the primary component for a smart HEMS architecture

Cypress Semiconductor, a global semiconductor company, defines the local controller as a "human machine interface (HMI), which is a wirelessly/wired communication feature to control and display the energy consumption data of electrical equipment" (Cypress

Semiconductor, 2019). Most importantly, every electrical equipment in the home needs to communicate with the central unit in order to maintain a comprehensive log of each of the appliance consumption data and tailor it to utility services and applications.

Smart Plug

The smart plug is the vehicle that connects appliance consumption data to the local controller. By providing this valuable service to a HEMS architecture, energy-consuming appliances can communicate to the local controller and the optimization services it provides. Intelligent appliances, or smart devices, are generally connected to other devices or networks via different wireless protocols, such as Wi-Fi, that can operate interactively and autonomously.

Nuri Telecom, a South Korea-based smart grid and energy management technology vendor, explains how a smart plug serves as an electricity meter and control device for appliances connected to the power outlet in order to wirelessly interconnect them to the local controller. "The smart plug is placed between the appliance and the outlet. The plug measures the electricity consumption, not just the total amount of electricity consumed in a billing period, but precisely when the electricity was used" (Nuri Telecom, 2019).

End-Use Appliance

The final component of the communication network of the HEMS architecture is the end-use energy consuming appliance. The following are several examples of energy-using appliances that are relatively common in a residential household: space heating, space cooling, water heating, refrigeration, cooking, clothes dryers, freezers, lighting, clothes washers, dishwashers, television and related equipment, computers and related equipment, and furnace fans and boiler circulation pumps.

An important distinction is that many of these load appliances are ideally under a priority setting, which is intended to provide the residential end-user comfort that high priority load is not disrupted. In other words, “residents are able to assign priority for each electrical appliance through the related smart plug to pursue their comfort in the residential unit (Shakeri et al., 111, 2018). By prioritizing appliances, any inconvenience, due to delay or violation of system preferences, such as price- or demand-based incentives, are accounted for and leveraged as a means for providing a more effective customer experience that requires minimal to no effort on the part of the user.

II. Business Services and Applications

Now that this paper has discussed what a home energy management system is at a system level and at a component level, it is time to analyze the different business services and applications a HEMS can provide, including logging, control, and management functions.

In order to effectively deploy HEMS functions, such as business services and applications, each home appliance must have a power control, sensing, and communication capability. In this case, each home appliance should be able to self-identify, i.e., distinguish itself from other appliances. As Teng and Yamazaki (2019) state, “the key assumption is that each appliance has a specific profile of energy consumption and a schedule tolerance that allows its energy consumption profile to be shifted. The problem to address is how to find a set of shift times that achieves the lowest total cost of energy consumption” (Teng and Yamazaki, 40, 2019). To dive deeper into this perspective, this paper will focus on three core business services, logging, control, and management, which will answer a series of questions, including (1) is the appliance’s consumption meaningful, (2) is the appliance powered by electricity or non-electricity sources, and (3) is the appliance both shiftable and non-disruptive.

Logging

The logging function collects and saves the data on the amount of electricity usage from individual appliances, including information on the status of power infrastructure and dynamic pricing. In particular, the logging capabilities are traditionally served through advanced metering infrastructure (AMI). AMI is a foundational aspect of the logging function because of the need for the utility service provider to be able to have access to your energy consumption patterns. The U.S. Energy Information Administration (EIA) defines AMI as "a device that measures and records electricity usage at a minimum of hourly intervals and that provides the data to both the utility and the customer at least once a day. Installations can range from basic hourly interval meters to real-time meters with built-in two-way communication capabilities that can record and transmit real-time data" (U.S. EIA, 2019).

With regards to demand response and dynamic pricing, there are a series of financial incentives that provide a tailored choice architecture for the residential consumer. Choice architecture plays on the theory of loss aversion by creating a model for framing a set of choices for the consumer. Not only is this approach important for encouraging consumers to become better acquainted with their home energy systems, it also serves as a stepping stone towards effective marketing strategies, which include time-of-use pricing (TOU), real-time pricing (RTP), variable peak pricing (VPP), critical peak pricing (CPP), and critical peak rebates (CPR).

- TOU – applies to usage over broad blocks of hours (e.g., on-peak = 6 hours for summer weekday afternoons; off-peak = all other hours in the summer months) where the price for each period is predetermined and constant.
- RTP – pricing rates generally apply to usage on an hourly basis.

- VPP – a hybrid of time-of-use and real-time pricing where the different periods for pricing are defined in advance (e.g., on-peak = 6 hours for summer weekday afternoons; off-peak = all other hours in the summer months), but the price established for the on-peak varies by utility and market conditions.
- CPP – when utilities observe or anticipate high wholesale market prices or power system emergency conditions, they may call critical events during a specified time period (e.g., 3 pm – 6 pm on a hot summer weekday) where the price for electricity during these time periods is substantially raised.
- CPR – when utilities observe or anticipate high wholesale market prices or power system emergency conditions, they may call critical events during pre-specified time periods where the price during these time periods remains the same but the customer is refunded at a single, predetermined value for any reduction in consumption relative to what the utility deemed the customer was expected to consume (DOE, 2019).

Control

This paper defines control as the exercise of restraint or direct influence over an appliance. The more meaningful the appliance, i.e., where a large amount of energy is consumed on a daily basis relative to other end uses, the greater opportunity for control functions to play an impactful role.

Control is also uniquely influenced depending on whether the appliance is powered by electric or non-electric sources of energy. This is important because there is a growing trend of distributed energy resources, such as solar PV or energy storage, that are either complementing or supplementing the electricity grid. Depending on the meaningfulness and source of power for each appliance, the control function can operate the device, or devices, based on both time and price variables, e.g., via the electricity grid, on-site solar PV, energy storage, or all three combined.

With regards to combining the three sources of power supply, intelligent control algorithms could potentially customize the state of appliance in the household with what is available between the grid, solar PV, and storage. As Shakeri (2017) states, "throughout the day, a control algorithm aggregates information from the electrical appliance, the status of the battery, and the price of electricity from the grid. When a user tries to turn on the appliance, the load controller receives the request in accordance with either the price or source. At the time the signal is received, the control algorithm checks the status of the battery, and if the battery has enough charge to support the appliance, then the power is drawn from the storage device and distributed to the appliance for consumption" (Shakeri, 158, 2017).

Management

This paper defines management as the process of interrelating the supply and demand of energy with the most effective time of day, price of power, or personal preference for the end-use. More specifically, optimizing both supply and demand is focused around the concept of real-time energy management, "which uses real-time algorithms to shift the controllable appliances to get two important aims, i.e., reducing the peak to average ratio in load demand and reducing the electricity bills" (Shakeri et al., 155, 2017). The HEMS management function is most effective when the appliance is both shiftable and non-disruptive, which are defined by the following:

- Shiftable Appliance – the electrical energy consumed by appliances can be delayed, such as the washing machine or clothes dryer. In other words, their electrical energy requirement can be postponed with regard to time of day or price of power.
- Non-Shiftable – the electrical energy consumed cannot be delayed, such as the refrigerator or freezer. Appliances that are non-shiftable are unable to move consumption to another time of the day or when there is a change in the price of power. The refrigerator is an effective example because if it is turned off over a period of time, the consumer's food could spoil.
- Disruptive Load Management – the deliberate interference of a residential end-user's use of appliance with no regard for the user's preference or comfort. For example, cutting off access to cooking during peak-demand hours without notifying the user of the loss of service can reduce the consumer's ease of living, because the consumer expects the cooking appliance to work on-demand. Likewise, the user might prefer to wash their clothes at particular times, e.g., the afternoon instead of early in the morning.
- Non-Disruptive Load Management – the deliberate interference of a residential end-user's use of appliance with regard for the user's preference and comfort. For example, turning on the water heating appliance early in the morning instead of at peak-hours without notifying the end-user. In this context, the water is still heated without any disruption to the consumer's ease of living.

On the topic of real-time energy management, the New York Research and Development Authority (NYSERDA) made a clear distinction as to how real-time energy management differs from the traditional utility meter approach. For example, utility bills are conventionally released every 30 days, and the data received by the utility does not explicitly state where or how the energy is being consumed. Real-time energy management, on the other hand, is “a cutting-edge technology that continuously sends a building’s live and historical performance data to an advanced cloud-based system that provides a series of services, including fault detection, diagnostics, predictive analytics, and performance optimization capabilities” (NYSERDA, 2019).

There are many benefits to having real-time energy management services. They improve situational awareness of the building’s operations, tailor system preferences to comforting the customer, and enable productive use of energy with little to no waste. More specifically, real-time energy management turns raw data into actionable information that could eventually cut the homeowner out of the decision-making process by using predictive analytics to automate how the logging, control, and management functions operate.

This paper just explained a series of business services and applications a utility or third-party service provider could include in their service offering. This paper will now discuss how a HEMS service operates using an average household’s energy consumption profile and the different variations of HEMS based on geography and climate.

Methods

In order to evaluate how an average household currently uses energy broken down by end-use appliance, this paper gathered data from the U.S. Energy Information Administration (EIA, 2019). EIA supplies energy load data through the Annual Energy Outlook (AEO) with historical reference data for delivered energy, including for both electricity and non-electricity sources.

The EIA AEO data starts with total surveyed households broken down by type, including single family, multi-family, and mobile homes. There were 82 million single family homes, 31.25 million multi-family homes, 6.4 million mobile homes, and a total of 120.35 million homes surveyed altogether. The U.S. Census Bureau's data from 2018 has 138,537,078 total households in the United States, so EIA's data corresponds to roughly 87 percent of the total U.S. households. The specific end-use appliances in the AEO reference data is broken down into a number of end-use categories, including space heating, space cooling, water heating, refrigeration, cooking, clothes dryers, freezers, lighting, clothes washers, dishwashers, television and related equipment, computers and related equipment, and furnace fans and boiler circulation pumps.

The data for each end-use appliance is given in quads per year for all the households combined. For the purpose of this paper, the data is broken down to kilowatt-hours (kWh) per day per household using excel spreadsheets. After the analysis was conducted for the average household, this paper then leveraged the literature review of the relevant business services and applications to prepare an evaluation

After analyzing how a HEMS service operates using an average household's energy consumption load profile, this paper then analyzed the data at a more granular level. This detailed section compared (1) the Northeast and West geographic regions of the United States and (2) hot-humid and very cold-cold climatic regions of the United States to see what additional insights can be drawn. The data for this section is sourced from the U.S. EIA's Residential Energy Consumption Survey (RECS), which is a nationally representative sample of housing units, including energy characteristics on the housing unit, usage patterns, and household demographics. This information is combined with data from energy suppliers for these homes to estimate energy costs and usage for heating, cooling, and other end-use appliances.

The data for the Northeast begins with the census for both the New England and Middle Atlantic regions. The New England census consists of 5.6 million surveyed households, while the Middle Atlantic region consists of 15.4 million surveyed households. Combined, the total surveyed households in the Northeast region is 21 million. For energy and electricity consumption, the data is broken down by kWh per year per total surveyed households, which is then analyzed into kWh per day per household. For non-electricity consumption, the data begins in British thermal units (Btu) per year per total surveyed households, which is then analyzed to kWh per day per household.

The data for the West region begins with the census for both the Mountain and Pacific areas. The Mountain census amounts to 8.5 million surveyed households, while the Pacific census amounts to 17.9 million surveyed households. The total amount of surveyed households for the West region is 26.4 million. The energy and electricity consumption data are initially shared in kWh per year per total surveyed households, but the data was then analyzed down to kWh per day per household. The non-electric data begins in Btu per year per total surveyed households, but it was then analyzed to kWh per day per household.

The final part of the analysis section dealt with a comparison of two climatic regions, hot-humid and very cold-cold. Both climatic regions factor in location and season, but they do not list individual states or geographic areas, only those related to the climate. There are 22.8 million surveyed households for the hot-humid climate region and 42.5 million surveyed households for the very cold-cold climate region. For both regions, the energy and electricity consumption data were referenced as kWh per year per total surveyed households, but the data was then broken down to kWh per day per household. The non-electric data was referenced as Btu per year per total surveyed households and broken down to kWh per day per household.

The geographic and climatic regional analysis includes data for the following end-use appliances: space heating, space cooling, water heating, refrigeration, cooking, clothes dryers, freezers, lighting, clothes washers, dishwashers, and television and related equipment. Each of the appliances were analyzed within an excel spreadsheet.

Results

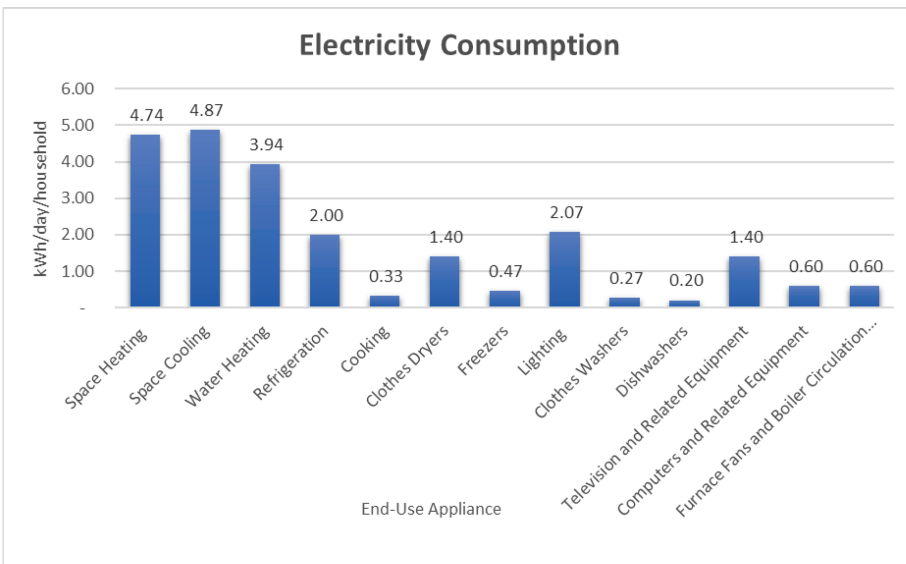
I. Average Household

Table 1 is a breakdown of the energy consumption figures for each end-use appliance for an average household based on residential consumption data broken down to kWh per day per household. As can be seen, the highest consuming appliances are those related to space heating, space cooling, and water heating that together make up about 84 percent of the total energy consumption profile for an average residential household. The remaining end-use appliances, including refrigeration, cooking, clothes dryers, freezers, lighting, clothes washers, dishwashers, television and related equipment, computers and related equipment, and furnace fans and boiler circulation pumps only make up roughly 16 percent of the remaining total energy consumption per kWh per day per household.

Energy Consumption (by end use)	(kWh/day/household)
Space Heating	36.69
Space Cooling	5.27
Water Heating	11.41
Refrigeration	2.00
Cooking	1.13
Clothes Dryers	1.60
Freezers	0.47
Lighting	2.07
Clothes Washers	0.27
Dishwashers	0.20
Television and Related Equipment	1.40
Computers and Related Equipment	0.60
Furnace Fans and Boiler Circulation Pumps	0.60
Total	63.71

(Table 1, Average Household – Energy Consumption)

Although the highest energy consuming appliances are both space and water heating, which are respectively 36.69 and 11.41 kWh per day per household, they are primarily powered by non-electric sources of energy, such as natural gas or propane. This is shown in figure 5, below, where both space and water heating combined only consume on average 8.68 kWh of electricity per day per household, which is roughly 18 percent of their combined energy consumption. Space cooling, on the other hand, consumes 4.87 kWh per day per household of electricity, which is 92% of its total energy consumption. This method of calculating electricity to energy ratios is important when considering HEMS services and will be further discussed later in this paper.



(Figure 5, Average Household – Electricity Consumption)

The total amount of electricity consumption in the energy load portfolio is about 22.88 kWh per day per household, which is only a little more than one-third the amount of the total energy consumed. The heating and cooling appliances, i.e., space and water heating and space cooling, amount to about 60 percent of the total electricity consumption. The remaining high electricity consuming appliances, including refrigeration, clothes dryers, lighting, and television and related equipment, amount to roughly 30 percent of the total electricity consumption profile on a kWh per day per household basis.

End-Use	Electricity:Energy Ratio
Space Heating	13%
Space Cooling	92%
Water Heating	35%
Refrigeration	100%
Cooking	29%
Clothes Dryers	88%
Freezers	100%
Lighting	100%
Clothes Washers	100%
Dishwashers	100%
Television and Related Equipment	100%
Computers and Related Equipment	100%
Furnace Fans and Boiler Circulation Pumps	100%
Total	36%

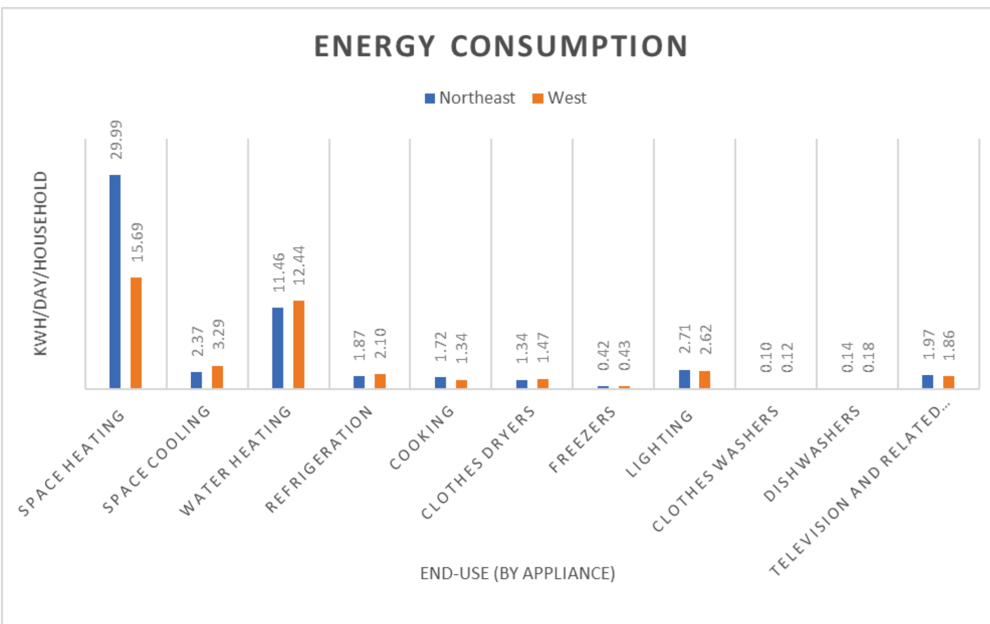
(Table 2, Average Household – Electricity : Energy Ratio)

Another method for evaluating both the electric and non-electric sources of energy for each end-use appliance is to calculate the electricity to total energy ratios. As can be seen in table 2, above, space heating is less than 15 percent of the electricity as it relates to the total energy consumption on a kWh per day per household basis. Water heating and cooking also consists of less than 50 percent of the average household's use of energy with regards to electricity ratios. On the other hand, space cooling, refrigeration, clothes dryers, freezers, lighting, clothes washers, dishwashers, television and related equipment, computers and related equipment, and furnace fans and boiler circulation pumps all have high electricity to energy ratios, with the lowest being clothes dryers at 88 percent.

II. Regional Analysis

Northeast vs. West

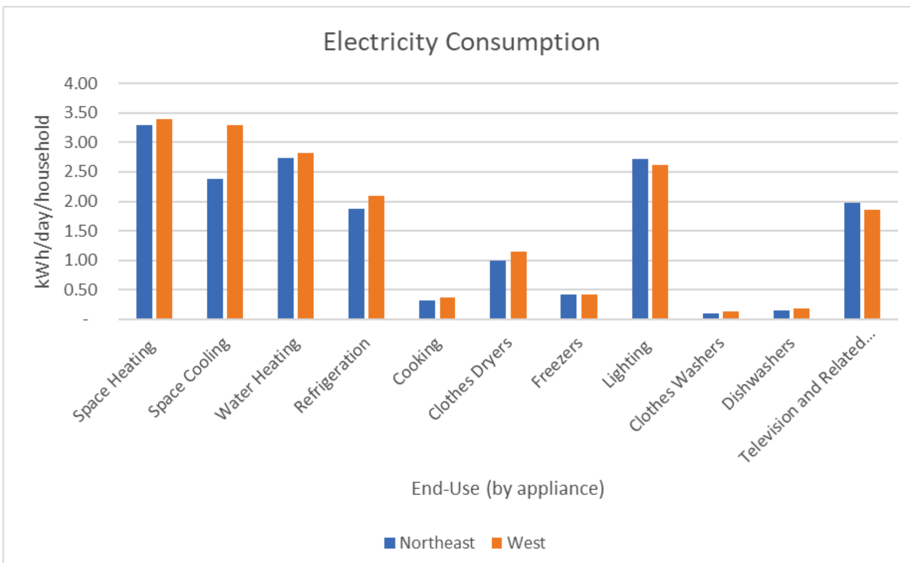
As demonstrated in figure 6, below, the two primary energy-consuming appliances are space and water heating, which is very similar to the average household's energy consumption profile. There are, however, unique regional differences around space heating. The Northeast region, in particular, consumes space heating by almost double the amount as in the West. For example, space heating in the Northeast averages about 30 kWh per day per household, while the average in the West is only about 15 kWh per day per household.



(Figure 6, Northeast – West Energy Consumption)

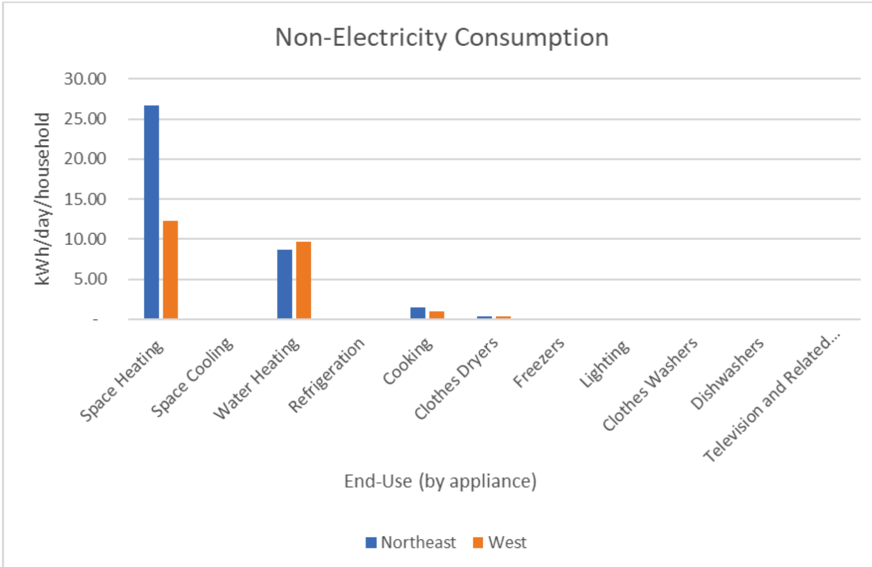
When it comes to water heating, the West is marginally the higher-consuming region. Despite this difference, the rest of the appliances are roughly equal; therefore, the greatest divider in energy consumption between the two regions is space heating.

Figure 7 portrays the electricity consumption data for each end-use appliance between the Northeast and the West. As can be seen, the space heating category, which is the primary differentiator between the two regions, is the higher electricity consuming appliance in the West than in the Northeast. This is interesting because the West uses more electricity across the entire load portfolio, including for space cooling, water heating, and refrigeration. Although the Northeast consumes more electricity for lighting and television and related equipment, there is not very much variability across both regions on a kWh per day per household basis.



(Figure 7, Northeast – West Electricity Consumption)

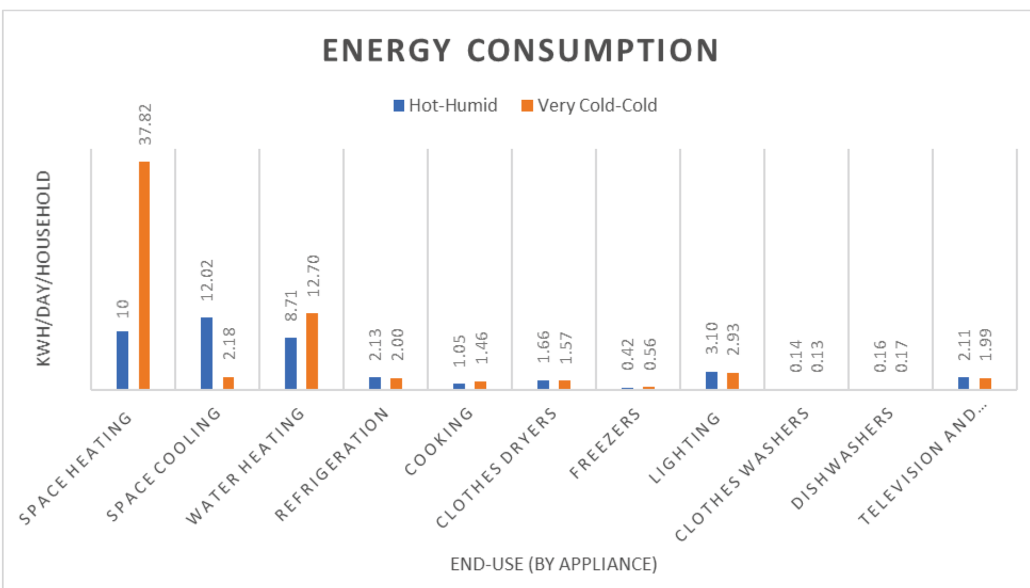
Figure 8 shows how space and water heating are primarily powered by non-electric sources of energy, such as natural gas and propane. Despite both appliance's meaningful consumption, the Northeast is far greater in powering space heating with non-electric sources than the West. This is important because it is quite different than the average electricity consumption for both regions where space heating consumed roughly 3.29 kWh of electricity per day per household. In this case, the Northeast consumed an average of 26.70 kWh of non-electricity per day per household for space heating.



(Figure 8, Northeast – West Non-Electricity Consumption)

Hot-Humid v. Very Cold-Cold

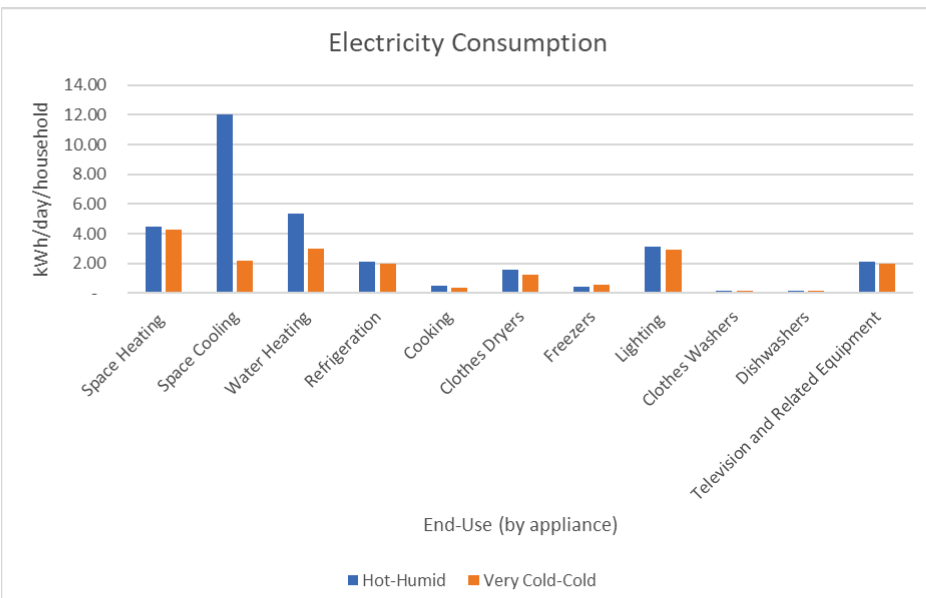
With regards to the second comparison between the two climatic regions, hot-humid and very cold-cold, there is a wide variation between space heating and cooling.



(Figure 9, Hot-Humid – Very Cold-Cold Energy Consumption)

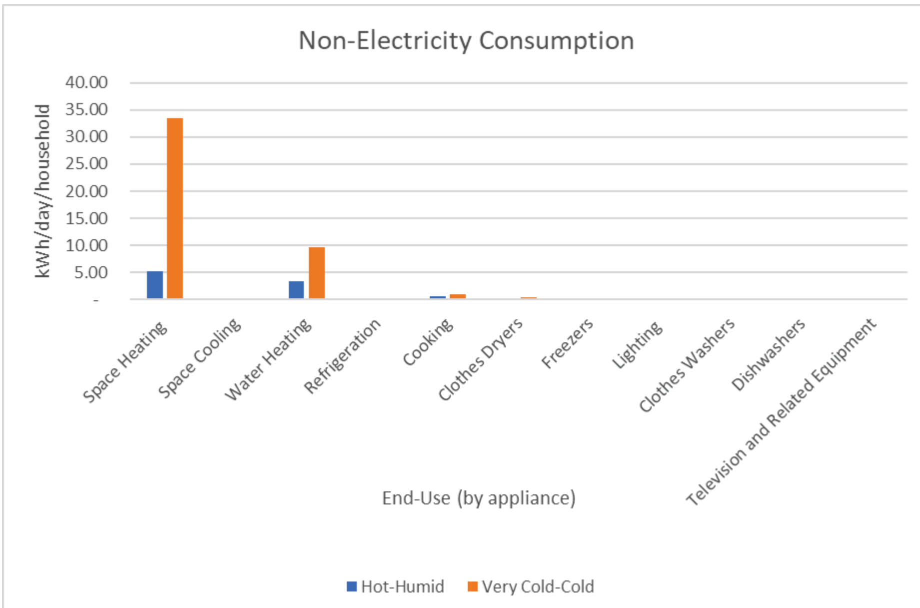
Figure 9 shows that colder regions consume more energy on space heating, while hotter and humid regions consume more energy for space cooling. More specifically, cooler regions, on average, consume roughly 37.82 kWh per day per household on space heating, and hotter regions consume roughly 12.02 kWh per day per household on space cooling.

Figure 10 demonstrates the level of electricity consumption for each end-use appliance, and as can be seen, the hot-humid region uses a significantly higher amount of electricity when it comes to space cooling. In particular, the hot-humid region consumes 100 percent electricity for their space cooling consumption, which is 12.02 kWh per day per household. On the other hand, the very cold regions only consume 4.27 kWh of electricity per day per household for space heating, which only amounts to 11 percent of the appliance's total energy consumption.



(Figure 10, Hot-Humid – Very Cold-Cold Electricity Consumption)

Figure 11 presents space heating as the highest-consuming non-electric appliance in cold regions on a kWh per day per household basis. This is important because, as demonstrated in figure 10, space heating was not the highest consuming electric appliance, but in this instance, space heating consumes more than 33.54 kWh of non-electric energy per day per household in the cold regions. This is much higher than the warmer regions where space heating only consumes 5.27 kWh of non-electric energy per day per household.



(Figure 11, Hot-Humid – Very Cold-Cold Non-Electricity Consumption)

Discussion

I. Average Household

As analyzed, the highest energy-consuming appliances for an average household are primarily heating appliances, e.g., space and water heating. Although space cooling also plays a role, this paper showed in table 1 that the consumption profile is marginal when compared to the heating profile. This is important because of an aforementioned discussion around tailoring a HEMS architecture to the most meaningful, or highest-consuming, appliances. In other words, although space cooling, refrigeration, clothes dryers, lighting, and television and related equipment present fruitful targets for HEMS services, the space and water heating appliances are the highest-consuming appliances, which makes them a unique opportunity.

For the second question of electricity- and non-electricity-powered appliances, space and water heating are primarily powered with non-electric sources. Therefore, on-site solar PV, which generates electricity rather than non-electric sources of energy, such as natural gas or propane, may not be suitable for accommodating a HEMS architecture tailored to existing heating appliances. Despite this point, the U.S. EIA recently presented data that demonstrates a trend towards the electrification of heating in the residential household. “From 2005 to 2015, the share of U.S. homes using electricity for their main heating equipment increased from 30 percent to 36 percent, with the share of homes using electricity for their main water heating increasing from 39 percent to 46 percent” (EIA, 2019). This data point is promising for the future fully-electrified home, including HEMS opportunities in providing logging, control, and management capabilities for the average residential household’s heating appliances. In the meantime, space cooling, refrigeration, clothes dryers, lighting, and television and related equipment are all mostly, or totally, powered by electricity, so they present the most effective opportunity for a solar PV-tailored HEMS architecture for existing households.

A final reason for expanding HEMS architecture to space and water heating is because they are both shiftable and non-disruptive, including the fact that heating can be captured inside the home over a longer period of time. For example, space and water heating can be turned on when the user is not home and perform its heating function for when the user arrives; therefore, the appliance is shifted in the time of use and does not disrupt the daily user’s ease of living. Space cooling, clothes dryers, and lighting are also shiftable and non-disruptive, so they are good opportunities for a HEMS architecture. On the other hand, refrigeration is both non-shiftable and disruptive, and television and related equipment is disruptive; therefore, this paper argues that a HEMS architecture would not be suitable for these appliances.

It is important to mention, however, that the HEMS service is primarily designed around the user, so the user is ultimately in control of when and how the appliance operates. The HEMS service, and specifically the management business function, is serving a supporting role in the customer experience, so if a customer wants to override any components or apply an ad hoc approach to energy management, they are in their power to do so. A HEMS service, on the other hand, is most effective when decision-making is driven both by reducing peak demand and lowering energy consumption costs, so a user must weigh both the positives and negatives when deciding to override the HEMS.

II. Regional Analysis

The electricity to energy ratios in the Northeast and West regional comparison showed how space heating is also the primary factor for differentiating between the two, which is important because it demonstrates an opportunity for the Northeast if the electrification trends or real-time energy management capabilities are expanded for a HEMS architecture.

Other than the space heating component, there are opportunities for a HEMS architecture around water heating and space cooling. For example, both appliances are shiftable and non-disruptive, so logging functions, such as real-time pricing and time of use pricing, can help consumers more effectively appropriate stored electricity to reduce the costs and minimize the risks of being caught in a high peak time. Space cooling is particularly interesting because it is fully electric and can be tailored to solar PV or energy storage technology. Therefore, both regions could enable a HEMS service to reduce energy use at peak times by using more solar generated electricity instead of from the electricity grid, via control functions.

Moreover, lighting, refrigeration, clothes dryers, and television and related equipment are mostly or fully electric, so these appliances also present significant opportunities when tailored to a HEMS architecture. Although they are not as valuable of opportunities as compared to the heating or cooling appliances, both lighting and clothes dryers are shiftable and non-disruptive, so they meet the criteria for effective HEMS services. On the other hand, refrigeration is both non-shiftable and disruptive, and television and related equipment is shiftable but disruptive; therefore, it may not meet the consumer's preferences for a HEMS architecture with minimal interference to the user's ease of living.

With regards to the second comparison between the two climatic regions, hot-humid and very cold-cold, there are similar instances with the aforementioned analysis on both space heating and cooling. As discussed, they both demonstrate valuable opportunities because of the series of business services and applications that can be tailored to each climate region. For example, very cold regions consume nearly 37.82 kWh per day per household for space heating as compared to the 10 kWh per day per household in hot and humid regions, which is nearly four times the amount. On the other hand, hot and humid regions consume nearly 12.2 kWh per day per household for space cooling as compared to the 2.18 kWh per day per household consumed in the very cold regions, which is nearly six times the amount.

Within the electricity consumption conversation, the hot-humid region uses a significantly higher amount of electricity when it comes to space cooling. Therefore, this is a ripe opportunity for a HEMS to tailor the service offering and provide a financial incentive, e.g., a critical peak pricing or time of use pricing effect, to shift the resource over to a more effective time of day. Also, since the resource is powered by electricity, shiftable, and non-disruptive, edge infrastructure, such as solar PV and energy storage, could adequately provide space cooling on demand, so even if a HEMS wanted to reduce dependence on the electricity grid, there wouldn't be any loss in reliability. This would fit perfectly during the hottest times of the day when the sun is shining and excess solar power is being generated on-site.

On the other hand, powering space heating in the very cold regions is still challenging due to them being non-electric sourced appliances. Similar to the Northeast region, consumers would need to continue the electrification trend, including substituting non-electric powered heating appliances to fully electric ones. One example of an electric heating appliance is an active solar heating system that "uses solar energy to heat either a liquid or air and then transfer the solar heat directly to the interior space or to a storage system for later use. Liquid-based active solar heating, in particular, would work well in residential households that already have boilers with hot water radiators or absorption heat pumps, which are becoming more common in cold regions" (DOE, 2019). This conversion would also provide an opportunity to tailor solar PV-enabled HEMS architecture and financial incentives, such as critical peak rebates, to reduce the amount of energy being sourced from the electricity grid during the high peak demand periods, which is advantageous considering both the shiftable and non-disruptive nature of space heating.

Due to the complicated nature of electrifying heating appliances, this paper would continue to suggest taking advantage of lower priority fully electric appliances, such as lighting, refrigeration, clothes dryers, and television and related equipment, which as demonstrated in figure 10, are all high-consuming electric appliances. In particular, lighting and clothes dryers are both shiftable and non-disruptive, and this makes them valuable opportunities for shifting their use to more effective times of the day. Both refrigeration and television and related equipment do not meet the aforementioned criteria of shiftability and non-disruptiveness, so this paper would argue against tailoring a HEMS architecture to these appliances.

By discussing these comparisons, this paper presented a new frame for both academic researchers and entrepreneurs to tackle global issues with more consumer-centric perspectives. As demonstrated, there are logging services that incentivize a change in behavior, control parameters that match demand with renewable resources, and mechanisms to provide real-time energy management capabilities. There are also significant trends in the electrification of heating appliances, which when fully delivered, can provide substantial energy savings in the residential household. With regards to the fully electric appliances, the regional analysis showed that space cooling, lighting, and clothes dryers are all both shiftable and non-disruptive, which meets this paper's criteria for effective HEMS architecture. On the other hand, both refrigeration and television and related equipment tend to interfere with the consumer's daily ease of living, so this paper does not support a HEMS architecture tailored to these appliances. By introducing all of these concepts, residential energy consumers, in general, can now be better aware of their consumption habits and in more control of how and when they use energy.

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